Effects of Board Surface Finish on Failure Mechanisms and Reliability of BGAs

Dr. Reza Ghaffarian, Ph.D.
Jet Propulsion Laboratory
California Institute of Technology
Tel: (818) 354-2059
email: Reza.Ghaffarian@JPL.NASA.Gov

Abstract

Ball Grid Array (BGA) is an important technology for utilizing higher pin counts, without the handling and processing problems of the peripheral array packages. The assembly reliability of BGAs was investigated under a JPL-led consortium. A large number of test vehicles with two ceramic (361 and 625 I/Os) and five plastic (256, 313, 352-two types, 560 I/Os) packages and three surface finishes were assembled and subjected to two thermal cycling environments. The number of cycles to failure was determined.

This paper will present cycles to failure in Weibull plots as well as their failure characteristics up to 7,000 cycles. The effect of surface finishes (HASL, OSP, and Ni/Au) on cycles to failures and their failure mechanisms will also discussed in details. The SEM microphotographs and elemental surface chemistry for random brittle failure of Ni/Au will be presented. Possible reasons for ductile and brittle failure behavior will also be discussed.

Introduction

Ball Grid Array (BGA) electronic packages are now become in common use for commercial applications and is being persuade actively by aerospace and military industry. These packages are replacing Quad Flat Pack (QFP) packages at higher pin counts. In addition to improved thermal and electrical performance, BGAs higher pitch (0.050 inch typical), better lead rigidity, and self-alignment characteristics during reflow processing make them also very attractive from the manufacturing aspects.

BGAs' solder joints cannot be inspected and many aspects of manufacturing including rework, and double sided assembly processing and their effects on reliability are not well characterized. In high reliability SMT assembly applications, e.g. space and defense, the ability to inspect the solder joints visually has been standard and has been a key factor in providing confidence in solder joint reliability.

Unlike commercial applications which measures reliability failures in parts per million, the acceptable risk for the success of a space mission is associated with the first failure of electronic parts or interconnection. In addition, every space mission is unique and the electronic boards are specially designed for specific missions. Space applications may range from shuttle missions lasting a few days to missions outer solar systems requiring multi-decade service life.

The difference in reliability requirements plays a key role in the selection/design and inspection/testing processes. Even though the highest reliability is demanded, it is extremely difficult to quantify the reliability level requirement and demonstrate its indices. One reason is due to the unavailability of solder joint field data and failure statistics. This limits the exact definition of reliability assurance, Assurance must depend on qualification testing methodologies unique to accelerated environments along with credible analytical prediction.

The current constraint on budgets and changes in military specifications along with the applications of bold new technologies for space missions necessitates the use of advanced commercial electronic packages. Use of advanced packages including BGAs and CSPs, specifically their plastic versions, are contingent upon resolution of many issues of space applications such as radiation damage and consideration for thermal/vacuum environment.

To understand and address many common quality and reliability issues of BGAs, JPL organized a consortium with sixteen members in early 1995. Diverse membership including military, commercial, academia, and infrastructure sectors which permitted a concurrent engineering approach to resolving many challenging technical issues.

Interim test results presented previously [1]. This paper will discuss the following:

- The update cycles to failure test results in Weibull plots and failure mechanisms to about 7,000 cycles
- Differences in ceramic and plastic package failure mechanisms
- The effect of three types of surface finishes on failures and failure mechanisms

The finish effect will be emphasized. The surface finishes included: (1) Hot Air Solder Leveling (HASL), the predominant surface finish in industry; (2) Organic Solder Preservative (OSP), the new and cost-effective coating; and (3) Ni/Au, an application specific finish.

Generally, ceramic assemblies with different surface finishes showed similar ductile (creep) failure mechanisms when subjected to -30°C to 100°C cycles. Unexpectedly brittle failures were observed in two instances. One was noticed during a routine visual inspection and the other when the package subjected to pull tests after cycling exposure. Visual inspections were verified by cross sectioning and observation at higher magnifications using Scanning Electron Microscopy (SEM). The SEM microphotographs and element surface chemistry will be presented. Possible reasons for ductile and brittle failure behavior will also be discussed.

BGA Test Vehicle Configuration

The two test vehicle assembly types were plastic (PBGAs) and ceramic (CBGAs) packages. Both FR-4 and polyimide PWBs with six layers, 0.062 inch thick, were used.

Plastic packages covered the range from OMPAC (Overmolded Pad Array Carrier) to SuperBGAs (SBGAs). These were:

- Two peripheral SBGAs, 352 and 560 I/O
- Peripheral OMPAC 352 I/O, PBGA 352 and 256 I/O
- Depopulated full array PBGA 313 I/Os
- 256 QFP (Quad Flat Pack), 0.4 mm Pitch

In SBGA, the IC die is directly attached to an oversize copper plate providing better heat dissipation efficiency than standard PBGAs. The solder balls for plastic packages were eutectic (63Sn/37Pb).

Ceramic packages with 625 I/Os and 361 I/Os were also included in our evaluation. Ceramic solder balls (90Pb/10Sn) with 0.035 inch diameters had a high melting temperature. These balls were attached to the ceramic substrate with eutectic solder (63Sn/37Pb). At reflow, package side eutectic solder and the PWB side eutectic paste will be reflowed to provide the electro-mechanical interconnects.

Plastic packages had dummy and daisy chains with the daisy chains on the PWB designed to be able to monitor critical solder joint regions. Most packages had four daisy chain patterns, 560 I/O had five, and the QFP had one.

Thermal Cycling

Two significantly different thermal cycle profiles were used at two facilities, conditions A and B. The cycle A conditions ranged from -30 to 100°C and had increase/decrease heating rates of 2°C and dwells of about 20 minutes at the high temperature to assure near complete creeping. The duration of each cycle was 82 minutes. The cycle B conditions ranged from -55 to 125°C. Cycle B could be also considered a thermal shock since it used a three regions chamber: hot, ambient, and cold. Heating and cooling rates were nonlinear and varied between 10 to 15 °C/min. with dwells at extreme temperatures of about 20 minutes. The total cycle lasted approximately 68 minutes. BGA test vehicles were monitored continuously to detect electrical failure and their failure mechanism were characterized. BGA test vehicles were continuously monitored through a LabView system at both facilities.

THERMAL CYCLING RESULTS

Figure 1 shows cycles to first failure for all plastic packages: PBGA 313 and 256, OMPAC 352, SBGA 352 and SBGA 560. The results are for assemblies on FR-4 and Polyimide PWBs. Preliminary results for two assemblies showed generally higher cycles to failure for polyimide under the B conditions [1]. The most recent PBGA 313 assemblies that failed under the cycle A conditions are also included in the plots for comparison.

These plots were generated by ranking cycles to failures from low to high and then approximating the failure distribution percentiles using a median plotting position, $F_i = (i-0.3)/(n+0.4)$. No attempts were made to generate Weibull parameters since the sample sizes for B conditions was small and all assemblies under A conditions are being analyzed.

Several trends were identified. The PBGA 313, with a depopulated full array with solder balls under the die, were the first plastic packages to show signs of failure at both A and B cycling conditions. The scatter for both was narrow indicating large *m* Weibull parameter.

The next package assembly failure was SBGA 560. This package and the PBGA 256 with failure data at the extreme cycles showed very large scatter, indicating a low *m* value. Scatter in PBGAs, in general, could be attributed to slow failure progress. Scatter in failure data for SBGA 560 could be due to the immaturity of the package at the time of use. These packages were taken from those assembled in the early stage of production. The reasons for a large scatter for the PBGA 256 cycles to failure data are not known at this time.

Both OMPAC and SBGA 352 failed at later cycles than SBGA 560 and they were between a low tail for PBGA 313 and a high tail for PBGA 256. The 352 I/O package showed low scatter. Further test results being gathered and analyzed at JPL could shed some light on failure distribution and behavior on various plastic packages.

Effect of Ball Planarity on Failure

For assemblies under cycle A condition, a SBGA 560 package showed numerous electrical interruptions with signs of electrical opens at an unexpectedly low number of cycles (1,810 cycles). To assure failure, joints were die penetrated and tested to failure in pull testing. Stain on surface represents existence of crack prior to pull test. Fully covered stained area means joint failure. Photos of surface failures for 560 SBGA with stains are compared to a PBGA 313 in Figure 2. There much less stain on SBGA 560 that PBGA 313. Non of detached surfaces of SBGA 560 showed complete stains an indication of no joint failure. Detached surfaces also included a few pad pulling sites. Therefore, it was postulated that failure could have caused by package internal daisy chain possibly by die debonding or other package internal failure mechanisms.

Solder joints were detached from package, board, and board traces. The majority of detachments were from the package side- 468 out of 560. This means only 92 (560-468=92) detached from the board side in which 22 were from the board traces. The 70 (92-22) solder detached surfaces were randomly distributed. Randomness thought to be due non-optimum solder joints formed from the distribution tail of ball height variation. If this postulate is true, then the solder height distribution for the balls that separated at the board interface should be different from those that separated at the package interface.

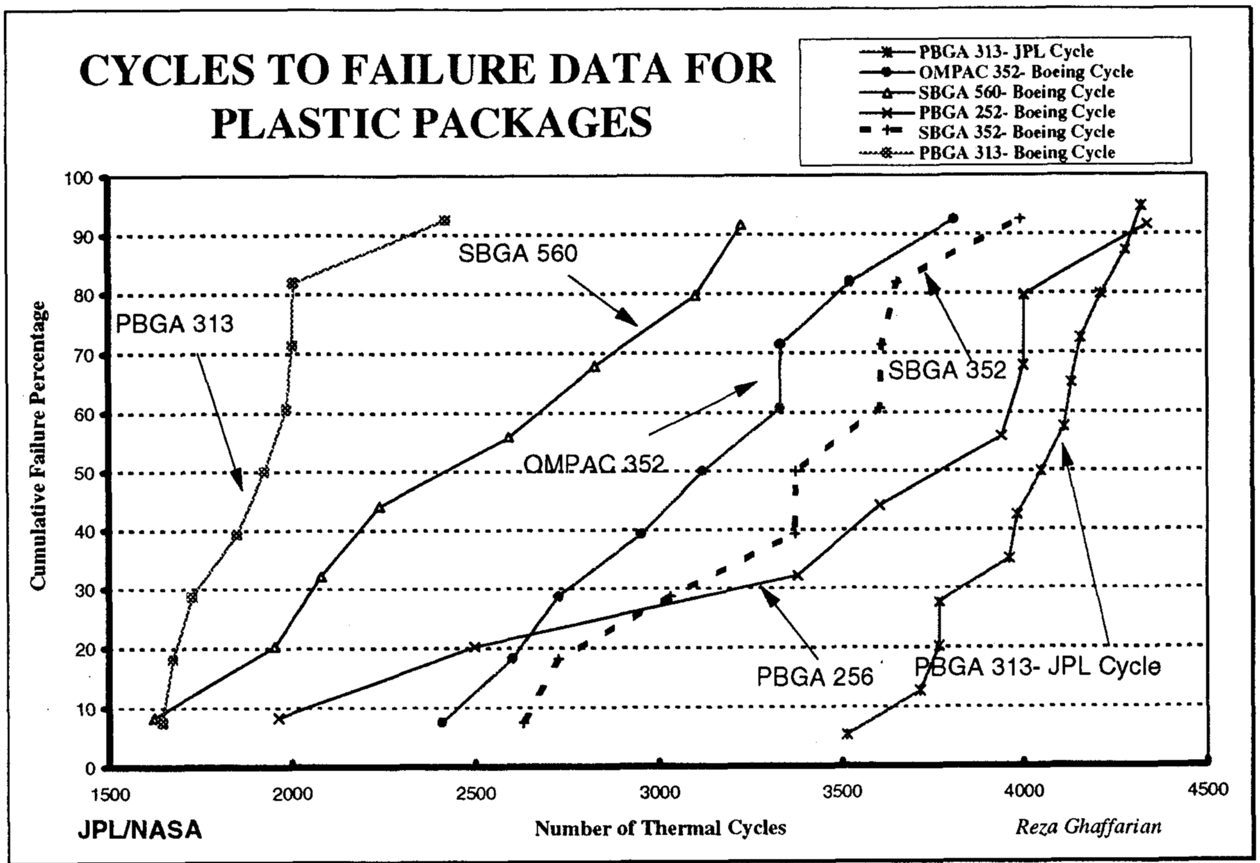
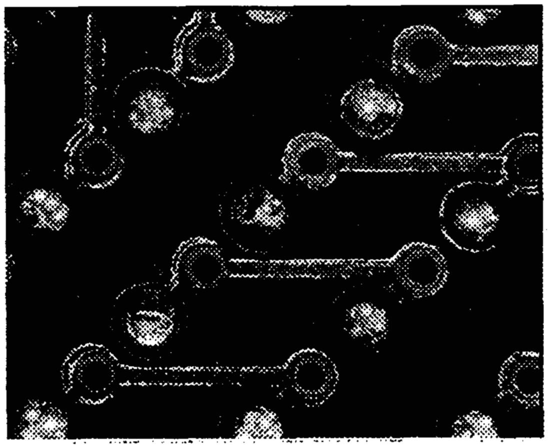
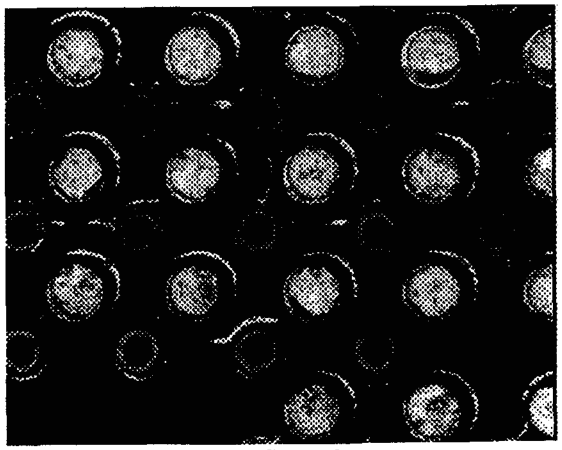


Figure 1 Cumulative Cycling to Failure for PBGA Assemblies (Cycle B) and PBGA 313 (Cycle A)



PBGA 313



SBGA 560

Figure 2 Crack Propagation (Stained) of PBGA 313 and SBGA 560 after 1,810 A Cycles.

We were able to verify this postulate since we had documented package ball height and location for each package prior to assembly. Solder ball heights were measured using a 3-D laser system. Then, planarity of each ball calculated using the height of the ball minus the height of the virtual seating plane generated by the three tallest balls. The ball planarity distribution for this specific SBGA560 package is shown in Figure 3. This figure also include planarity distribution for joints separated at the board interface.

Planarity distributions for both all balls and those failed from the board under pull test are similar. Planarities were in the range of 0.5 to 4 mils, averaging at 2.5 mils. For this specific package, it was concluded that there was no strong correlation between site separation and solder ball heights. This exercise did not consider the effects of package warpage and its distribution as well as localized board warpage distribution. Most probably either of these variables would have caused a more localized rather than random separation distribution.

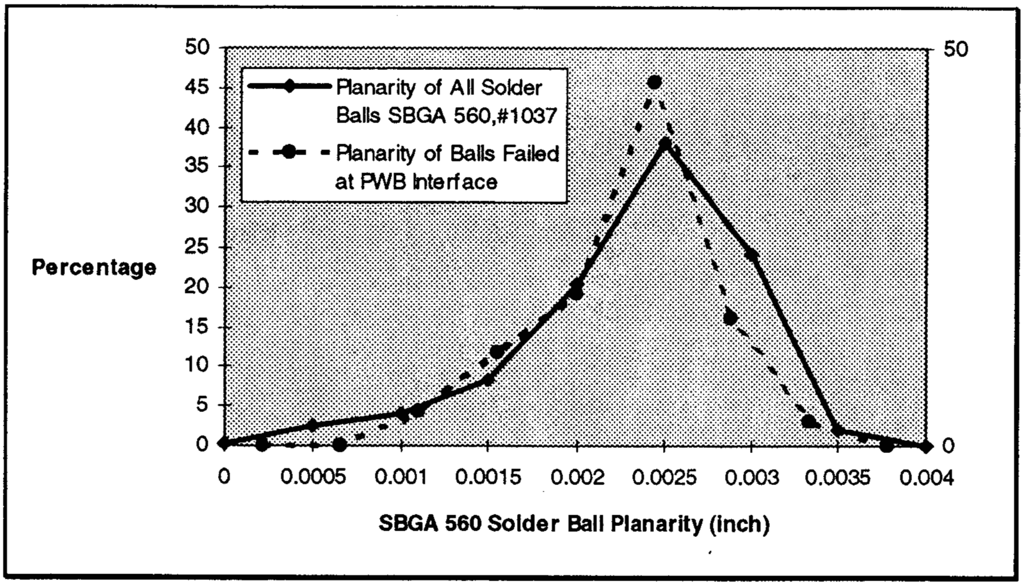


Figure 3 Solder Height Variation of Solder Balls for Board and Package Interface Failure for a SBGA

Failure Mechanisms for Plastic Assemblies

Among the plastic packages, the PBGA 313 with depopulated full array balls was first to fail under both B and A thermal cycling conditions. Figure 6 shows various cross-sections of this package's balls from corner to the center at 4,682 A cycles. These photos are for the balls under the die where most damages occur due to local CTE mismatch. Photos with and without voids were also included for comparison. Voids appear to have concentrated at the package interface under the die. Cracking occurred at package or board interfaces for solder balls with or without voids.

The voids were connected to interface not apparent from photos of cross-section, but it is evidenced from the seepage of mounting materials into voids. Except for the interface connecting cracks, there appeared to be no crack propagation among the voids. The solder joints for this package were also visually inspected to identify indicators of defects. There were none apparent. Even when these were inspected at 100x by SEM, no gross damage was observed, as evidenced from the top left SEM photo of Figure 4.

Figure 5 includes a collection of SBGA and PBGA solder joints with voids at different locations in the solder joints. Similarly to PBGA 313, most of voids are close to the package side. There is also an indicator of how cracks propagate in and out of the void. For the upper right hand photo of this figure, a crack initiated at the package interface and propagated into a void at a 45 ° angle. There is another void which is parallel to the package interface. The two types of cracks represent a mix mode stress condition.

Note also that the large void in the lower left photo shows evidence of mounting materials from metallugraphic preparation. This is puzzling since there is no evidence of a through-crack. Perhaps a crack, normal to the photograph's cross section, has interconnected the void to the outer balls' surface. Again, this reveals the complexity of failure modes and remind us of caution that must be exercised when interpreting failures by two dimensional cross-sectioning. Ideally, a three dimensional characterization is need to better interpret the results.

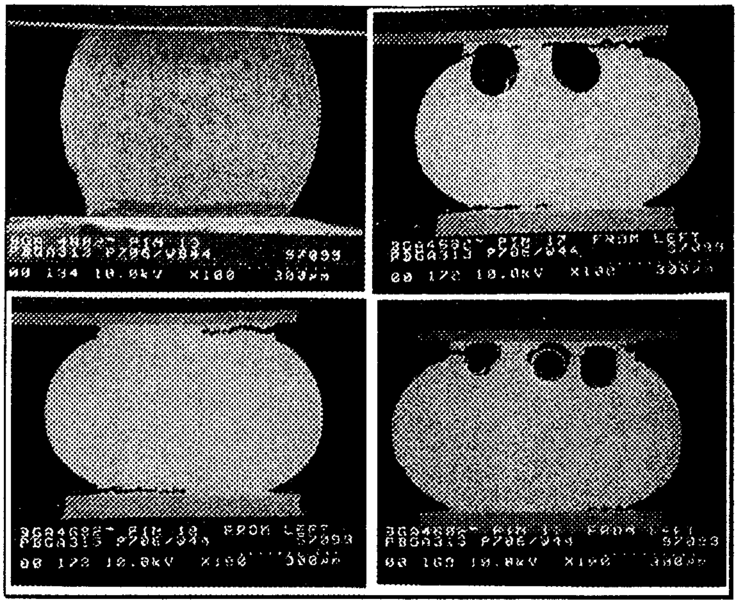


Figure 4 SEM and Cross-sections of PBGA 313 after 4,682 cycles under A (-30°C to 100°C) Conditions

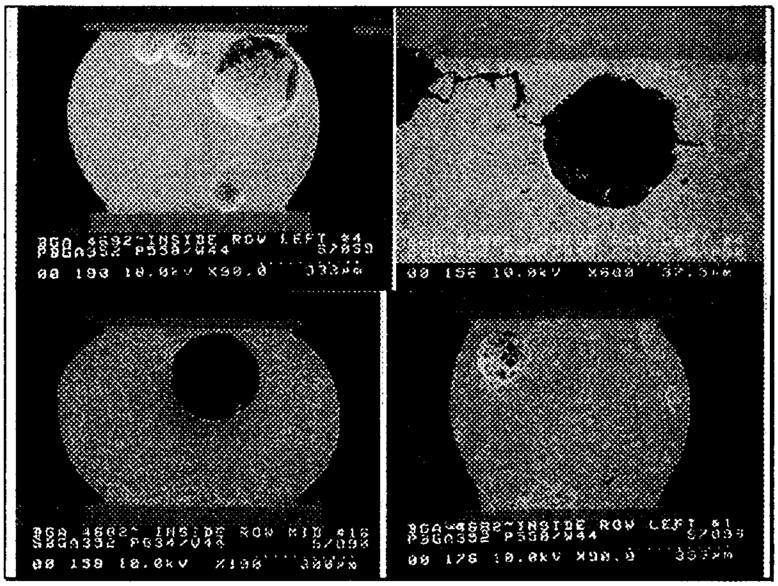


Figure 5 Voids in PBGA. Cross-section photos for PBGA 352 and SBGA 352 of Solder Balls with Void and Cracking after 4,682 cycles (-30°C to 100°C)

Package attachment were very weak after 4,500 B cycles and were easily detached from the board. Cycled packages were detached and balls were inked and their images were mapped. The ball map distributions for several detached PBGA 313 I/O packages shown elsewhere [2] and for SBGA560 are shown in Figure 6. All joint failures were not from the board interface and there appeared to some trend in their distribution.

Most balls were separated from the board interface for SBGA560 on FR-4 boards as evidenced from the large number of dark spots which represents the balls on the package. This is not true for those on polyimide board. More joint separations at the package side for polyimide board, might be due to higher thermal stability of polyimide compare to FR-4 in the B thermal cycle.

Note also, separation of one whole edge row from the package side. This might represents the existence of high warpage for outer package edge generally observed for the plastic packages. Similarly, mappings for other plastic packages were carried out and trends were studied.

For ceramic packages, mapping was not possible since most of the packages were already separated from the board at 4,500 cycles. Separations were mostly at the package interfaces since detached packages generally had no balls on them. In addition, several test vehicle boards had a large number of balls on the location of ceramic package attachments.

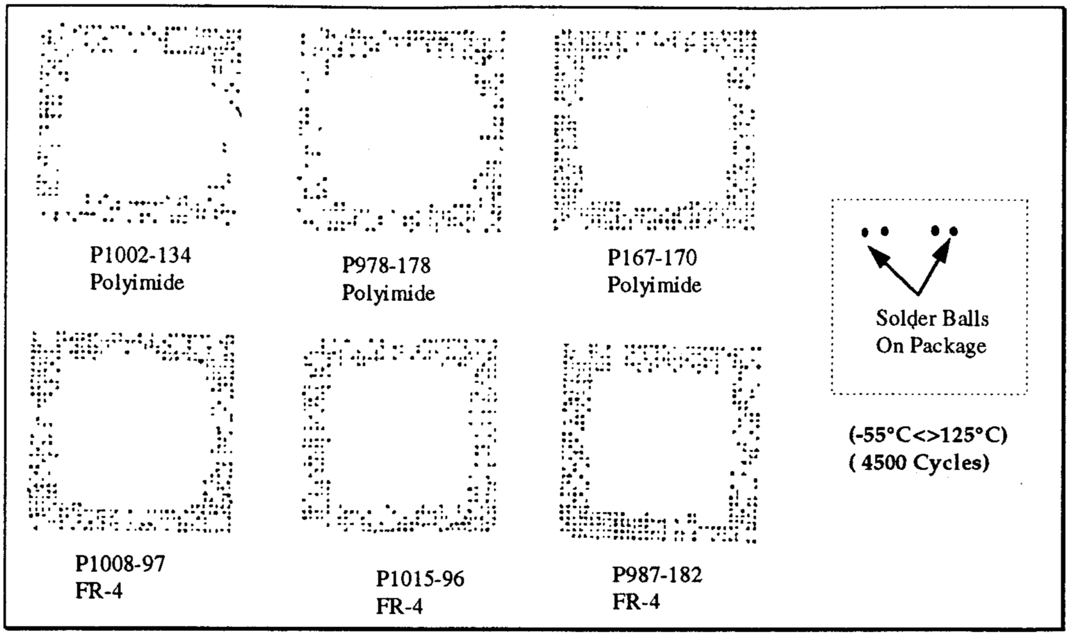


Figure 6 Map of board/package failure sites for SBGA 560 after 4,500 B cycles. Packages were detached and solder balls on package were then mapped

Surface Finishes

The surface finishes considered for evaluation were 180 TVs with Organic Solderability Preservative (OSP), 14 electroless nickel/immersion gold, and 5 HASLs. The critical process factors for BGA assembly as well as reliability issues were considered during the selection of surface finish. Factors such as surface coplanarity, solder volume, solderability, moisture sensitivity, thermal aging behavior (shelf life) and second reflows were also considered when the PWB surface finishes were selected.

HASL

The predominant surface finish in the PWB industry has been HASL. In HASL, the tin/lead plating is accomplished by dipping the fluxed PWB into or by passing it over molten solder. The excess solder is removed by high velocity hot air which levels the remaining solder on exposed surfaces. The solder coatings are dense and have good adhesion, but are non-uniform and are not suitable for some emerging technologies.

This process is being replaced for several reasons including environmental and safety issues (hazardous waste/lead exposure), technological limitations (fine pitch device assembly), and equipment maintenance expenses. Alternate processes have been developed that are environmentally friendly, and provide a surface planarity equivalent to the plated copper finish, and require very little equipment maintenance.

OSP

OSPs, also known as anti-tarnish, are gaining popularity as a low-cost, high volume alternative to HASL and provide excellent surface coplanarity required for fine pitch SMT applications. They are water based organic compounds (typically azole- benzotriazole or benzimidazole) that selectively bond with copper to provide an organometallic copper layer. OSP process temperatures usually do not exceed 150 °C, markedly lower than HASL process temperatures. Key drawbacks of OSPs include susceptibility to stain (water, flux, fingerprint) and deterioration as a result of temperature heat cycles typically found in mixed technology.

For example, compatibility of OSP finish with aramid PWB might be an issue. This is primarily due to the hydroscopic nature of aramid which requires prebaking at high temperature before reflow. This process degrades the OSP. Another issue that must be considered is compatibility of OSP with flux. Water soluble finishes are more likely to form solder balls if the temperature profile and solder mask design are not optimized. No clean flux with use of nitrogen atmosphere flow might be the choice for some applications.

The OSP materials recommended by the PWB fabrictor, was chosen for the test vehicle surface finish. The fabricator had used the coating for various BGA applications with no reported problems. One advantage of this coating was its more tolerant to higher temperatures commonly experienced during the drying stage.

Vendor data sheets indicate that the coating is a water-based OSP used to protect and maintain the solderability of printed circuit board copper surfaces. The active ingredient is designed to react with copper and copper alloys forming a thin uniform coating on circuitry. It is also report that the coating was compatible with R, RMA, OA, No-Residue, and No-Clean solder pastes and fluxes. It has excellent solder wetting even after multiple reflow operations. Thickness is typically 6-8 microinch (0.15 to 0.18 micron).

Ni/Au

Although electroless nickel/immersion gold are more complex than OSP, they satisfy the application-specific requirements for fine pitch and chip-on-board (COB) assemblies. This process is a two-layer, gold-over-nickel metallic surface finish plated onto the copper base by chemical vapor deposition. Nickel is deposited on copper by an electroless process resulting in a deposit thickness of 100 to 200 microinches.

The gold is then deposited in an exchange reaction replacing nickel on the entire surface with a thin layer of pure gold. The gold thickness is typically in the range of 3 to 5 microinches. Even though the gold thickness is not significant compared to that typically used for solder paste volume, the potential of solder joint embrittlement due to formation of intermetallic compounds with tin may be of concern. Ni/Au coatings are not reworkable, and are relatively expensive in terms of waste treatment and processing. The thickness of the gold was 3-5 microinches. Ni/Au surface finish was carried out by the same company that did the OSP coating.

Failure Mechanisms For Different Surface Finishes

Ceramic package failure under A cycling condition for PWBs with different surface finishes are shown in Figure 7. Both HASL and OSP failures, initiated at the PWB side, showed ductile features evidenced from the zig zag propagation through the eutectic solder joint. Generally, this was not the case for Ni/Au. For Ni/Au, several joints of a package showed brittle failure, which were first noticed during a routine visual inspection of assemblies.

Brittle failure by the gold embrittlement could be one possible explanation, if the amount of gold exceeded three volume percentages of the solder joint. This is not the case, since the thickness of gold was controlled by immersion technique to 3-5 µinch. To assure this was the case, a sample joint of Ni/Au surface finish was analyzed for various trace elements at PWB interfaces using the Energy Spectroscopy for Chemical Analysis (ESCA) feature of SEM. A cross-section photo with elements in each phase shown in Figure 8. Qualitative elements detected by probing at various sections of the joint are also determined. No traces of gold was detected, possibly because the low amount of gold could have been dissolved during the reflow process. Other elements were as expected and included Cu, Ni, P, Pb, and Sn. Existence of phosphorus traces indicates the chemistry of the bath used for Ni plating. This element is found in a common chemistry used for the Ni surface finish.

Further Evaluation of Cause of Brittle Failure

Elemental characterization of brittle surfaces was obscured by the metallugraphic mounting materials. Results were not accurate. A virgin surface with the brittle behavior was needed for a more accurate surface analysis.

Remain of this package was pull tested under sustaining load of 7 Ib. The load was small and no separation was observed after two monts at room temperature. No separation also after 5 days exposure at 100°C under the same load. The package was finally pried off. This techniques was not attempted at the beginning in order to avoid potential damage to solder joint.

Out of 525 separated balls, only 13 balls remained on board and the majority (525-13= 512) were still attached to package. Out of 512 pad separation on board, 470 were pulled from traces and 42 were by solder joint separation. Out of these 42, only 3 pad showed partial signs of brittle failure. The crescent surfaces were from 1/3 to about 1/4 of the pad area.

Figure 9 shows the SEM photographs for brittle failure feature on ball and package pad. Figure 10 shows elemental analysis of the ball and pad surfaces by ESCA. For ductile failure regions, the elements were Pb and Sn of eutectic solder composition as expected. This was not the case for brittle surfaces. At the smooth ball surface, elements included Ni, P, and Sn whereas at the pad surface, they were mostly Ni. Pimples on the ball surface were Sn.

Failure of Plastic Package with Ni/Au, OSP, HASL

Figure 11, shows cross-sectional micrographs of PBGA 256 after 6,800 A cycles. Photos are for three types of surface finishes, OSP, Ni/Au, and HASL. The failure are very similar to those show previously for assemblies after 4,800 cycles with the OSP finish. There is no apparent differences on failure mechanisms among the three surface finishes. Ductile failure is the principal failure mechanism for the three surface finishes. Similarly to other Plastic packages, failures were either from package or board side. Generally, voids were accumulated at the package interface.

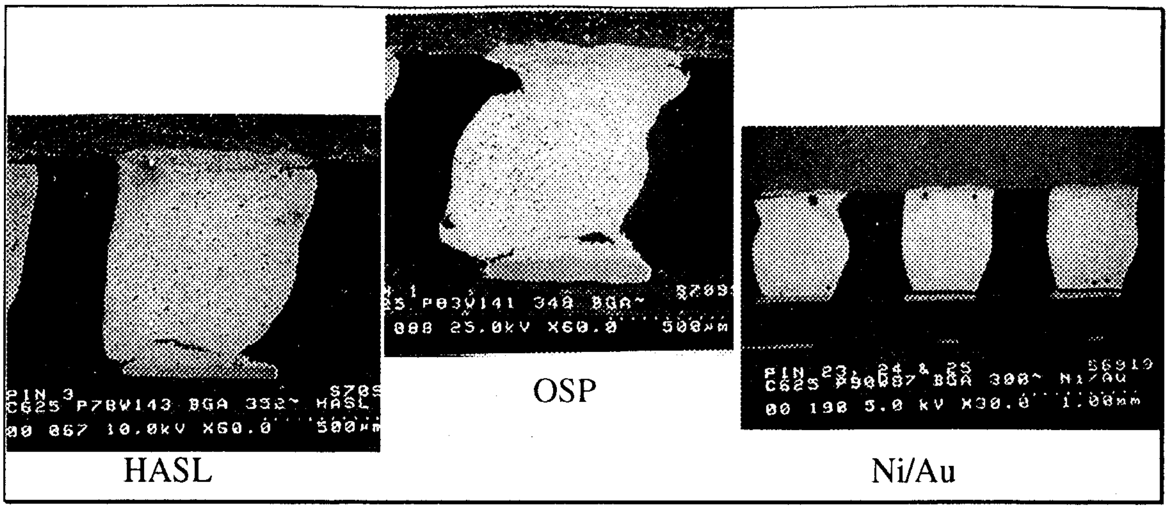


Figure 7 Failure Mechanisms for Joints on OSP, HASL, and Ni/Au Surface Finishes for CBGA 625 under A Conditions (-30°C to 100°C)

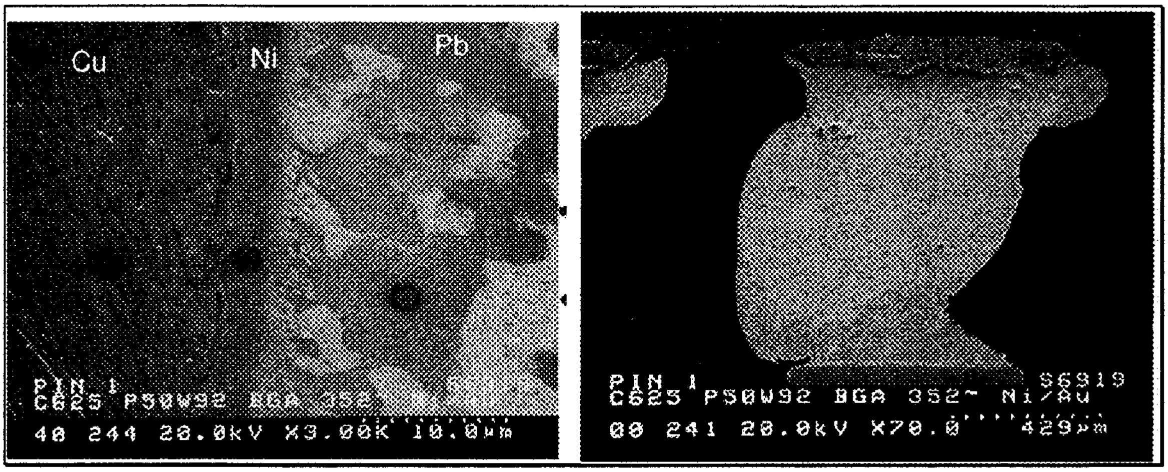


Figure 8 Magnified Photos of Ni/Au Interface Surface Finish

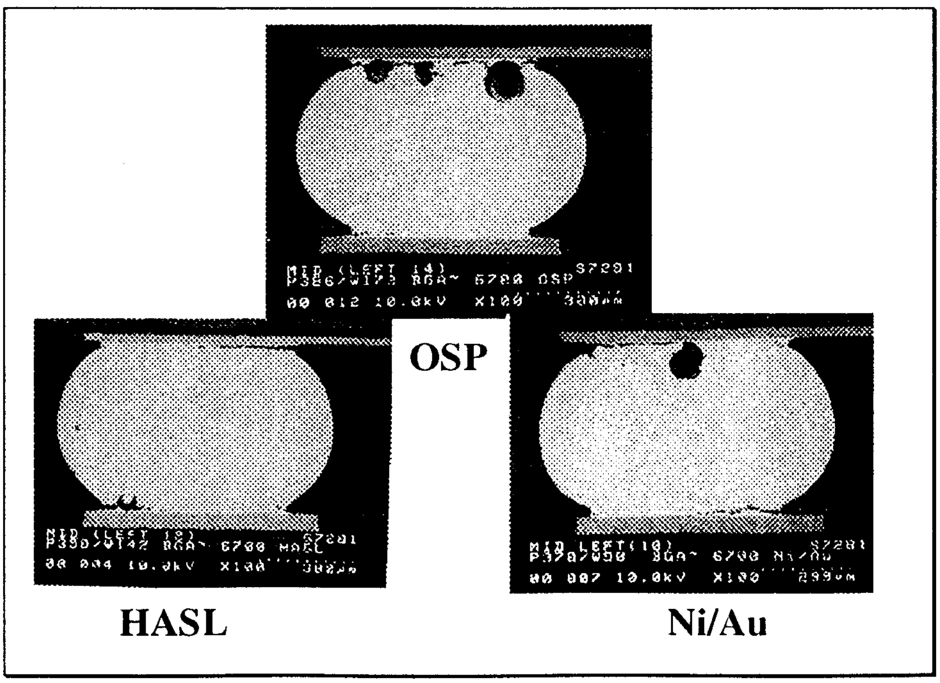
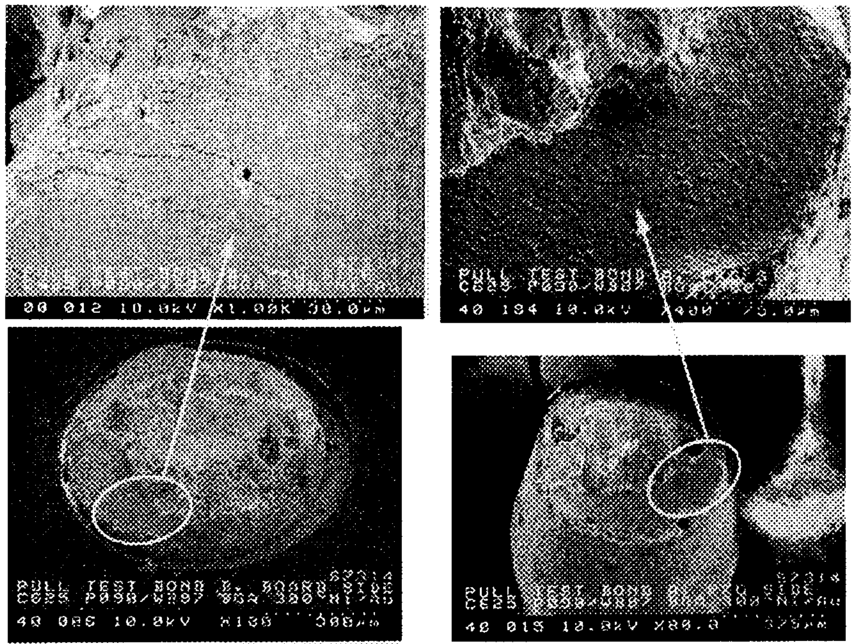
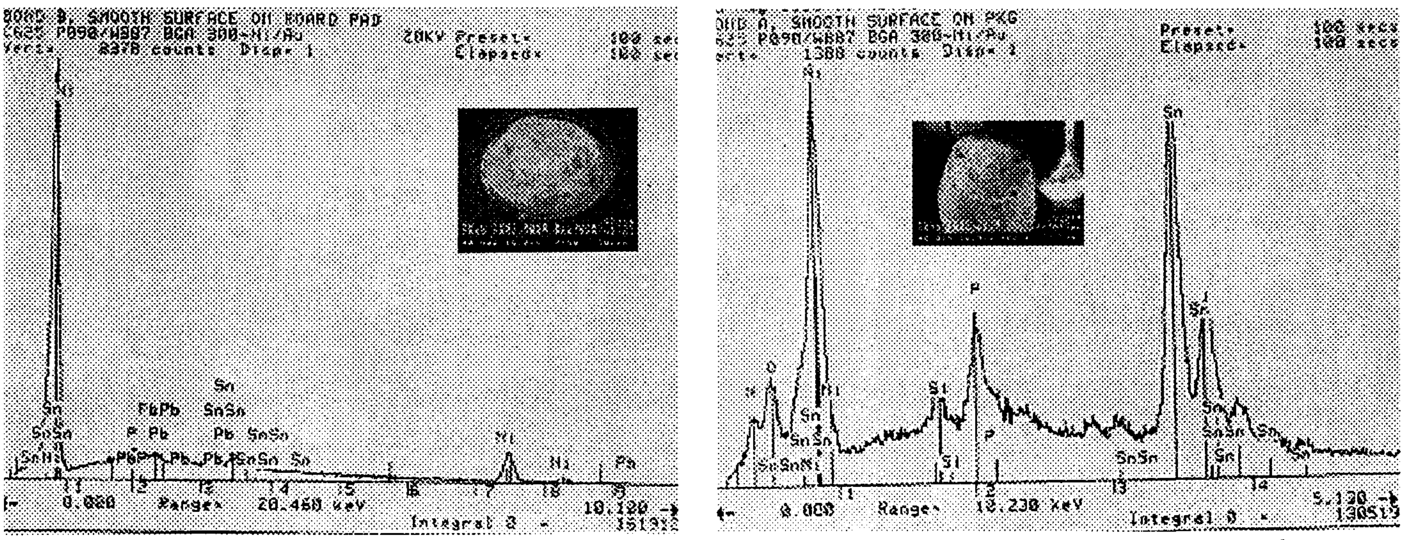


Figure 11 Surface finish and failure for PBGA 256 after 6,700 A cycles



Ni/Au, Board Failure Feature Ni/Au, Ball Failure Feature

Figure 9 SEM photomicrograph of detached of ceramic package on Ni/Au surface finish with brittle areas



Ni/Au, Board Surface Chemistry Ni/Au, Ball Surface Chemistry

Figure 10 Elemental chemistry of brittle surface shown in Figure 9

CONCLUSIONS

Assembly Reliability

- Plastic assemblies with I/Os from 254 to 560 on FR-4 and Polyimide PWBs, showed an order of magnitude larger number of cycles to failure than ceramic assemblies with I/Os from 361 to 625. They were in thousands of cycles for plastics whereas in hundreds for ceramics, in cycling temperature ranges of -55 to 125 °C and -30 to 100 °C.
- The PBGAs with 313 I/O depopulated full arrays, were first among the PBGAs to fail (SBGA 560, SBGA 352, OMPAC 352, PBGA 313, and PBGA 256) with both cycling ranges (A and B conditions). It has been well established that this configuration, with solder balls under the die, is not optimum from a reliability point of view.

- For peripheral plastic packages, the size and number of I/Os appeared to be the key factors in cycles to failure for B conditions. As the size increased, cycles to failure decreased, i.e., the SBGA 560 was first to fail in this category and PBGA 256 was the last. These two assemblies also showed large scatters in cycles to failures. The reasons for the large failure scatters especially for the PBGA 256, are not well understood.
- A SBGA 560 package assembly showed numerous electrical interruptions with signs of electrical opens at an unexpectedly low number of A cycles (1,810). Destructive dye penetrant testing revealed no solder joint failure. It was postulated that failure could have caused by die debonding or other package internal failure.
- Pull testing performed on a SBGA 560 after 1,810 A cycles. Failure sites on board were identified and the distribution of solder ball height attached to these sites were compared to the distribution of all other balls. No correlation between height and failure sites was found.

Failure Mechanisms

- For plastic assembly, there were no indicators for early failure warning. This was not the case for ceramic packages. Indicators for CBGAs were due to differences in the metallurgy of ball and solder and also because the first signs of damages occur in the corner joints with the highest DNP. The ceramic joints showed signs of grain growth, pin hole formation, creeping, microcracking and cracking prior to failure.
- For plastic packages, crack initiation, propagation, and failure occurred at either the package or board interfaces for sections with or without voids. These were true for A or B cycle conditions. Generally, voids were concentrated near the package interfaces. There appeared to be no crack propagations among the voids, except for the voids interconnected at the interface..
- For a ceramic assembly failure, brittle failure was observed for Ni/Au surface finishes. OSP and HASL showed ductile failure through eutectic solder joint. For plastic packages, there were no distinction for the three surfaces.
- Pull test of assembly with Ni/Au brittle failure revealed only three localize brittle failure out 525 separated sites. This means potential of finding such random failure by a few cross-section examination is very low. Brittle failure has shown by bend test by others.
- Elemental analysis of one brittle Ni/Au surface finish revealed no detectable gold, but reasonable amount of phosphor and Ni on the detached solder ball surface. Phosphorous segregation at interface, surface contamination during Ni/Au plating or after plating by diffusion, and brittle fracture of Ni-P and Ni_3Sn_4 were shown the three potential of failure mechanisms [3]. This is for the case when the Ni/Au content is less than 1% and there is no potential of gold embrittlement.

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